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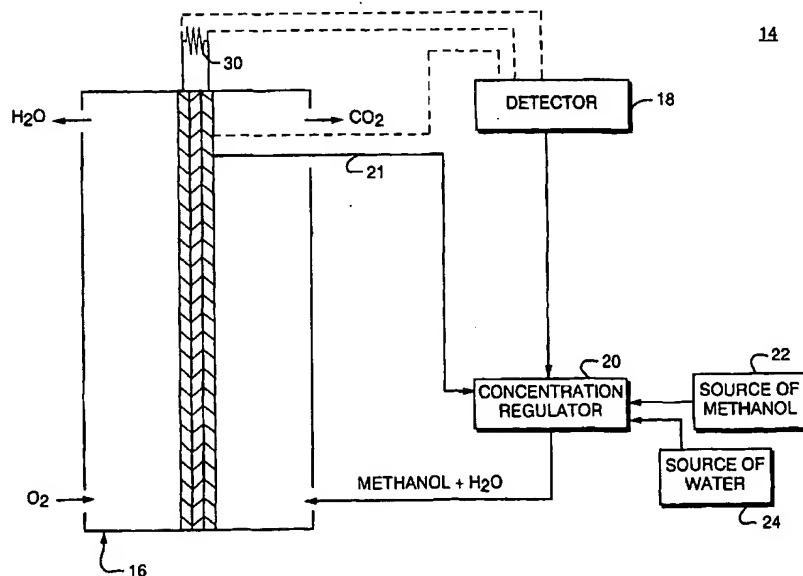
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(54) Title: APPARATUS AND METHODS FOR SENSOR-LESS OPTIMIZATION OF METHANOL CONCENTRATION IN A DIRECT METHANOL FUEL CELL SYSTEM



(57) Abstract: Apparatus and methods for regulating methanol concentration in a direct methanol fuel cell system without the need for a methanol concentration sensor. One or more operating characteristics of the fuel cell, such as the potential across the load, open circuit potential, potential at the anode proximate to the end of the fuel flow path or short circuit current of the fuel cell, are used to actively control the methanol concentration.

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# APPARATUS AND METHODS FOR SENSOR-LESS OPTIMIZATION OF METHANOL CONCENTRATION IN A DIRECT METHANOL FUEL CELL SYSTEM

## BACKGROUND OF THE INVENTION

### 5 *Field of the Invention*

The present invention relates generally to the field of fuel cells and, more specifically, to a direct methanol fuel cell system in which active control of the concentration of methanol at a critical point within the cell allows dynamic response to changes in power demand while minimizing crossover of methanol through the cell's membrane.  
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### *Background Information*

Fuel cells are devices in which an electrochemical reaction is used to generate electricity. A variety of materials may be suitable for use as a fuel, depending upon the materials chosen for the components of the cell. Organic materials, such as methanol  
15 or formaldehyde, are attractive choices for fuels due to their high specific energies.

Fuel cell systems may be divided into "reformer based" (*i.e.*, those in which the fuel is processed in some fashion before it is introduced into the cell) or "direct oxidation" in which the fuel is fed directly into the cell without internal processing. Most currently available fuel cells are of the reformer-based type, and their fuel processing  
20 requirement limits their application to relatively large applications relative to direct oxidation systems.

An example of a direct oxidation system is the direct methanol fuel cell system or DMFC. In a DMFC, the electrochemical reaction at the anode is a conversion of methanol and water to  $\text{CO}_2$ ,  $\text{H}^+$  and  $\text{e}^-$ . The hydrogen ions flow through a membrane  
25 electrolyte to the cathode, while the free electrons flow through a load which is non-

mally connected between the anode and cathode. At the cathode, oxygen reacts with hydrogen ions and free electrons to form water.

In addition, conventional DMFCs suffer from a problem which is well known to those skilled in the art: cross-over of methanol from the anode to the cathode through the membrane electrolyte, which causes significant loss in efficiency. Cross-over occurs because of the high solubility of methanol in the membrane electrolyte. In order to minimize cross-over, and thereby minimize the loss of efficiency, the concentration of methanol in the fuel feed stream is kept low (*e.g.*, below 1M) by dilution with water. However, dilution of the methanol introduces other disadvantages: (1) the fuel cell's construction becomes more complicated and costly because of the structures and processes needed to store and manage the water; and (2) the energy per unit volume of the fuel cell, which is a critical factor in terms of the fuel cell's potential commercial applications, is reduced.

Many important applications of DMFCs require that the power source be able to vary its output in response to constantly changing electrical loads. There is a direct relationship between the electric load and the amount of methanol consumed. As such, it is desirable to vary the amount of methanol that is fed into the fuel cell, to supply slightly more fuel to the fuel cell than is consumed by the reaction that generates electricity. However, supplying substantially more fuel than is required has several disadvantages: it increases methanol crossover, which decreases efficiency of the system; in an open anode configuration, it increases the amount of fuel that passes through without reacting, thus wasting fuel; and in a closed anode configuration, it increases the volume of unreacted fuel that must be recirculated, consuming energy and increasing the demands on the system.

It is known to those skilled in the art that conventional efforts to actively control the methanol concentration, for the purposes of regulating the power output of a DMFC system and minimizing cross-over, have been accompanied by another disadvantage. In order to effect control using conventional methods, a methanol concentration sensor must be provided, the presence of which tends to further increase the cost and complexity of the fuel cell system as well as introduce an additional component whose failure could significantly affect performance.

## SUMMARY OF THE INVENTION

The present invention provides a direct methanol fuel cell system in which the concentration of methanol supplied to the anode is actively controlled so as to optimize the performance of the system, and minimize cross-over, but without the need for a methanol concentration sensor. The present invention monitors one or more of the fuel cell's operating characteristics, such as the potential across the load, the open circuit potential or the short circuit current. A preferable choice of operating characteristic is one for which a known relationship exists between that characteristic and methanol concentration. In this fashion, the monitored characteristic may be used, directly or indirectly, to generate a control signal which is supplied to a regulator. The regulator, which is coupled to sources of methanol and water and responsive to the control signal, functions to increase or decrease the concentration of methanol supplied to the anode.

In a first embodiment, the potential across the load or fuel cell stack is detected. Periodically, the flow of methanol is reduced or interrupted. As the methanol concentration drops, the potential across the load drops. By measuring the time required for the potential to drop to a predetermined value or the rate at which the potential drops, an initial methanol concentration may be determined and used to calculate or retrieve from a memory appropriate values for adjusting the concentration.

In a second embodiment, the potential is detected at a portion of the anode which is proximate to the end of the methanol flow path. Because the methanol concentration is normally lowest at the end of the flow path, the proximate portion of the anode is highly sensitive to changes in methanol concentration. The detected potential is compared to a predetermined reference or to the potential at another point of the anode which is upstream in the flow path, the difference being used to adjust the concentration.

In a third embodiment, the load is periodically disconnected from the fuel cell, thereby creating brief periods of time in which the open circuit potential of the fuel cell is detected. The detected potential is stored and compared to a previously stored value which represents the detected potential at an earlier time or a predetermined reference. Because the fuel cell's open circuit potential decreases as a result of methanol cross-

over, the difference in the compared potentials may be used to adjust the methanol concentration.

In a fourth embodiment, the load is periodically short-circuited, thereby creating brief periods of time in which the short circuit current of the fuel cell is detected and stored. Because all of the current produced by the fuel cell passes through the short circuit, the stored value serves as an indicator of how much methanol is available to the anode at a given time. The stored value is compared to a reference and the difference used to adjust the methanol concentration.

### BRIEF DESCRIPTION OF THE DRAWINGS

The invention description below refers to the accompanying drawings, of which:

Fig. 1 is a block diagram of a direct methanol fuel cell known in the prior art;

Fig. 2 is a block diagram of a direct methanol fuel cell system constructed in accordance with a preferred embodiment of the present invention;

Fig. 3 is a block diagram of one embodiment of the sensor/detector shown in Fig. 2;

Fig. 4 is a flowchart of a first method of controlling methanol concentration in the fuel cell system of Fig. 2;

Fig. 5 is a flowchart of a second method of controlling methanol concentration in the fuel cell system of Fig. 2;

Fig. 6 is a flowchart of a third method of controlling methanol concentration in the fuel cell system of Fig. 2;

Fig. 7 is a block diagram of a direct methanol fuel cell system constructed in accordance with an alternative embodiment of the present invention;

Fig. 8 is a schematic diagram of the switch shown in Fig. 7; and

Fig. 9 is a flowchart of a method of controlling methanol concentration in the fuel cell system of Fig. 7.

## DETAILED DESCRIPTION OF AN ILLUSTRATIVE EMBODIMENT

Figure 1 shows a conventional direct methanol fuel cell 2 in which a housing 4 encloses a cathode 6, a membrane electrolyte 8 and an anode 10. A load 12 is connected across cathode 6 and anode 10. Methanol and water are introduced into the anode side of housing 4 while oxygen is introduced into the cathode side of the housing. The source of the oxygen is preferably ambient air, but it should be understood that other sources could be used. As a result of the reactions at the anode and cathode, free electrons flow from anode 10 through load 12 to cathode 6, while hydrogen ions flow from anode 10 through membrane 8 to cathode 6. So long as the reactions continue, a current is maintained through load 12.

Figure 2 shows a direct methanol fuel cell system 14 which includes a direct methanol fuel cell 16, like that shown in Figure 1, which provides electricity to a load 30. System 14 also includes a detector 18, a concentration regulator 20, a source of methanol 22 and a source of water 24, which may represent water generated on the cathode side, water from an internal source, or a combination of both. Detector 18 is coupled across load 30 or to one or more points in the interior of fuel cell 16 and, as described in detail below, functions to measure one or more operating characteristics that are either directly or indirectly indicative of the concentration of methanol within fuel cell 16. Detector 18 generates a control signal which is supplied to concentration regulator 20. Concentration regulator 20, via flow path 21, receives unreacted methanol and water from fuel cell 16. In response to the control signal, regulator 20 operates to adjust the concentration of methanol supplied to fuel cell 16.

Regulator 20 may be implemented using a metering valve, a pump, a combination of a valve and pump, or any of a number of other conventional devices which are capable of controlling a flow of liquid and compatible with the control signal generated by detector 18. It should be understood that while concentration regulator 20 is shown coupled to both sources 22 and 24, it is of course possible to control the concentration of methanol delivered to fuel cell 16 by regulating either the flow of methanol or water or both. Alternatively, the outputs of sources 22 and 24 may be coupled to flow path

21 and such outputs controlled directly by the control signal generated by detector 18, in which case concentration regulator 20 would not be needed.

Figure 3 shows one embodiment of detector 18. An analog to digital (A/D) converter 32 is connected to receive an analog signal (*e.g.*, a potential) from fuel cell 16. Converter 32 produces a digital output signal which is supplied to a microprocessor or microcontroller 34. Microprocessor 34 is connected to a random access memory (RAM) 36. Microprocessor 34 may also be connected to a read only memory (ROM) (not shown) or other ancillary circuitry depending upon the requirements of a particular application. By loading RAM 36 with appropriate instructions and data, microprocessor 34 may be programmed in a well known manner to adjust the methanol concentration using one or more of the methods described below in connection with Figs. 4-6.

It should be understood that a wide variety of other circuits or devices could be used for detector 18 depending upon which operating characteristic of the fuel cell 16 is of interest. For example, the combination of a half-wave rectifier and a comparator could be used to monitor a potential produced by the fuel cell 16, compare the potential to a reference, and use the difference as a control signal for methanol regulator 20.

With reference now to Figures 3 and 4, a first method for regulating methanol concentration is shown. At step 38, a timer is tested to determine whether time has expired. If the time has not expired, the process essentially waits. If the time has expired, which indicates that it is time for a possible methanol concentration adjustment, the process advances to step 40 where microprocessor 34, through its control signal to regulator 20, causes the flow of methanol to be reduced or interrupted. Next, at step 42, the potential across load 30 (Fig. 2) or, if desired, some portion of the fuel cell stack is monitored and converted by A/D converter 32.

The potential across the load exhibits a non-linear relationship with methanol concentration in which the potential decreases gradually as the concentration decreases over a certain range, followed by a rapid decrease as the concentration falls below a level needed to sustain an efficient reaction. At step 44, microprocessor 34 may measure the elapsed time between the interruption of methanol flow and the decrease of potential across the load or the rate of decrease of that potential. Next, at step 46, microprocessor 34 may either calculate or retrieve from a database or other data structure that



may be stored in RAM 36 a value to supply as the control signal to the concentration regulator. At step 48, microprocessor 34 signals regulator 20 to restore and adjust the flow of methanol or water to optimize the methanol concentration. Lastly, at step 50, the timer is reset and the process returns to begin again.

5        Figure 5 shows an alternative method for effecting methanol concentration control. Again, the process begins, at step 52, with a determination whether predetermined time period has expired. If so, the process proceeds to step 54 where the potential is monitored at an electrically isolated portion of the anode of the fuel cell that is proximate to the end of the methanol/water flow path (*i.e.*, the farthest point from where  
10    methanol/water mixture enters the fuel cell housing), and compared to a predetermined value or the potential across another portion of the fuel cell. That point is preferably chosen because the methanol concentration is normally lowest there and the proximate portion of the anode is therefore very sensitive to changes in concentration.

At step 56, the potential is compared to a reference (*e.g.*, a predetermined value  
15    stored in RAM 36 or possibly an earlier value of the monitored potential that was previously stored) and the difference, if any, is then used to signal regulator 20 to adjust the flow of methanol or water at step 58. At step 60, the timer is reset and the process begins again.

Figure 6 shows another alternative method for controlling methanol concentration. In this method, following the expiration of a time at step 62, the load is temporarily disconnected from the fuel cell 16. This may be accomplished by a microswitch or similar device (not shown) that is controlled by microprocessor 34. Next, at step 66,  
20    the open circuit potential of fuel cell 16 is monitored and stored. The open circuit potential of the fuel cell is of interest because that potential decreases as methanol crossover occurs.  
25    over occurs.

At step 68, the load is reconnected to the fuel cell 16. At step 70, the most recent value of the open circuit potential is compared to a previously stored value (or to a predetermined reference) and the difference, if any, is again used to signal methanol regulator 20 to adjust the flow of methanol or water as appropriate at step 72. At step  
30    74, the timer is reset and the process begins again.

Figures 7 and 8 show another alternative embodiment of the present invention in which a direct methanol fuel cell system 76 includes a circuit 78 for periodically short-circuiting load 30. A current measuring device 80 is connected in series with a switch 84, both of which are coupled to detector 18. When switch 84 is open, essentially all of the current generated by fuel cell 16 flows through load 30 in a normal fashion. Conversely, when switch 84 is closed, essentially all of the current generated by fuel cell 16 flows through current measuring device 80. An optional potential measuring device 82 is connected in parallel with load 30.

With reference now to Figures 8 and 9, an alternative method for controlling methanol concentration will be described. Following the expiration of a timer at step 86, switch 84 is closed thereby short-circuiting load 30. Device 80 measures the current flowing through the short circuit and generates a signal or value indicative of same which is stored by detector 18 at step 90. The short-circuit current is an indicator of how much methanol is available to the anode of fuel cell 16 and is thus useful in controlling methanol concentration.

Next, at step 92, the stored value is compared to a reference and, at step 94, the difference is used to adjust the flow of methanol as described above. At step 96, switch 84 is opened, effectively reconnecting load 30 to fuel cell 16. At step 98, the timer is reset and the process begins to repeat.

In accordance with yet another embodiment of the present invention, two or more of the foregoing methods may be combined. For example, using the circuit of Figure 8 including device 82, the methods of Figure 4 (using potential across load or a portion of the fuel cell stack) and Figure 9 (short circuit current) could be used together to control methanol concentration. Such combinations could provide redundancy or make possible more precise control of methanol concentration.

It should be understood that other operating characteristics of the fuel cell which have known or derivable relationships to methanol concentration may also be used with the present invention.

What is claimed is:

### CLAIMS

- 1 1. A method of regulating methanol concentration in a direct methanol fuel cell  
2 system comprising:  
3 providing a concentration regulator, coupled to a source of methanol or a source  
4 of water or both, and responsive to a control signal for increasing or decreasing the  
5 concentration of methanol supplied to a fuel cell;  
6 periodically short-circuiting a load driven by said fuel cell;  
7 sensing the short circuit current produced by said fuel cell;  
8 comparing said sensed current to a reference; and  
9 generating said control signal in response to said comparison.
- 1 2. The method as in claim 1 wherein one or more of said sensing, comparing and  
2 generating steps is performed by a microprocessor or microcontroller.
- 1 3. A direct methanol fuel cell system comprising;  
2 a direct methanol fuel cell;  
3 a source of air or oxygen coupled to the fuel cell;  
4 a source of methanol;  
5 a source of water;  
6 a detector for detecting changes in a short circuit current produced by said fuel  
7 cell and responsively producing a control signal; and  
8 a concentration regulator coupled to the methanol source or to the water source  
9 or to both sources, detector and anode of said fuel cell, responsive to said control signal  
10 for varying the concentration of methanol in said fuel cell.
- 1 4. The system as in claim 3 wherein said concentration regulator comprises a me-  
2 tering valve, a pump, or a combination thereof.
- 1 5. A method of regulating methanol concentration in a direct methanol fuel cell  
2 system comprising:

3 providing a concentration regulator, coupled to a source of methanol or a source  
4 of water or both, and responsive to a control signal for increasing or decreasing the  
5 concentration of methanol supplied to a fuel cell;

6 sensing one of a group of fuel cell operating characteristics including potential  
7 across a load driven by said fuel cell, potential across a portion of a fuel cell stack, po-  
8 tential at a portion of an anode of said fuel cell which is proximate to an end of a  
9 methanol flow path, an open circuit potential of said fuel cell, a short circuit current of  
10 said fuel cell and, periodically, alternately sensing another one of said group of fuel cell  
11 operating characteristics; and

12 using said alternately sensed operating characteristics to control a concentration  
13 of methanol in said fuel cell.

1 6. A method of regulating methanol concentration in a direct methanol fuel cell  
2 system comprising:

3 providing a concentration regulator, coupled to a source of methanol or a source  
4 of water or both, and responsive to a control signal for increasing or decreasing the  
5 concentration of methanol supplied to said fuel cell;

6 periodically reducing or interrupting the amount of methanol supplied to said  
7 fuel cell; sensing a potential across a load connected to said fuel cell and determining  
8 an amount time needed for said potential to begin to decrease or a rate of decrease of  
9 said potential; and

10 using said determination to generate said control signal.

1 7. A method as in claim 6 wherein a potential across a portion of the fuel cell stack  
2 is sensed instead of the potential across said load.

1 8. A method as in claim 6 wherein one or more of said sensing, determining and  
2 using steps is performed by a microprocessor or microcontroller.

- 1 9. A method of regulating methanol concentration in a direct methanol fuel cell sys-  
2 tem comprising:  
3 providing a concentration regulator, coupled to a source of methanol or a source  
4 of water or both, and responsive to a control signal for increasing or decreasing the con-  
5 centration of methanol supplied to said fuel cell;  
6 sensing electric potential at a portion of an anode of said fuel cell which is proximate to  
7 an end of a methanol flow path;  
8 comparing said electric potential to a reference; and  
9 generating said control signal in response to said comparison.
- 1 10. A method as in claim 9 wherein one or more of said sensing, determining and us-  
2 ing steps is performed by a microprocessor or microcontroller.
- 1 11. A method of regulating methanol concentration in a direct methanol fuel cell sys-  
2 tem comprising:  
3 providing a concentration regulator, coupled to a source of methanol or a source  
4 of water or both, and responsive to a control signal for increasing or decreasing the con-  
5 centration of methanol supplied to said fuel cell;  
6 periodically disconnecting a load from said fuel cell and sensing an open circuit  
7 potential of said fuel cell;  
8 storing a value representing said sensed potential;  
9 comparing said stored value to a previously stored value which represents the  
10 sensed potential at an earlier time or to a predetermined reference; and  
11 generating said control signal in response to a difference between said compared  
12 values.
- 1 12. A method as in claim 11 wherein one or more of said sensing, determining and  
2 using steps is performed by a microprocessor or microcontroller.
- 1 13. A direct methanol fuel cell system comprising:

2           a direct methanol fuel cell;  
3           a source of air or oxygen coupled to the fuel cell;  
4           a source of methanol;  
5           a source of water;  
6           a detector for detecting changes in one or more operating characteristics of said  
7 fuel cell and responsively producing a control signal; and  
8           a concentration regulator coupled to the methanol source or to the water source or  
9 both sources, detector and anode, said regulator responsive to said control signal for  
10 varying the concentration of said methanol in said fuel cell such that cross-over of  
11 methanol is substantially minimized.

1   14.    The system as in claim 13 wherein said detector comprises an analog to digital  
2 converter coupled to receive a potential indicative of said one more operating character-  
3 istics, and a microprocessor or microcontroller, coupled to said analog to digital converter  
4 and a memory, for generating said control signal.

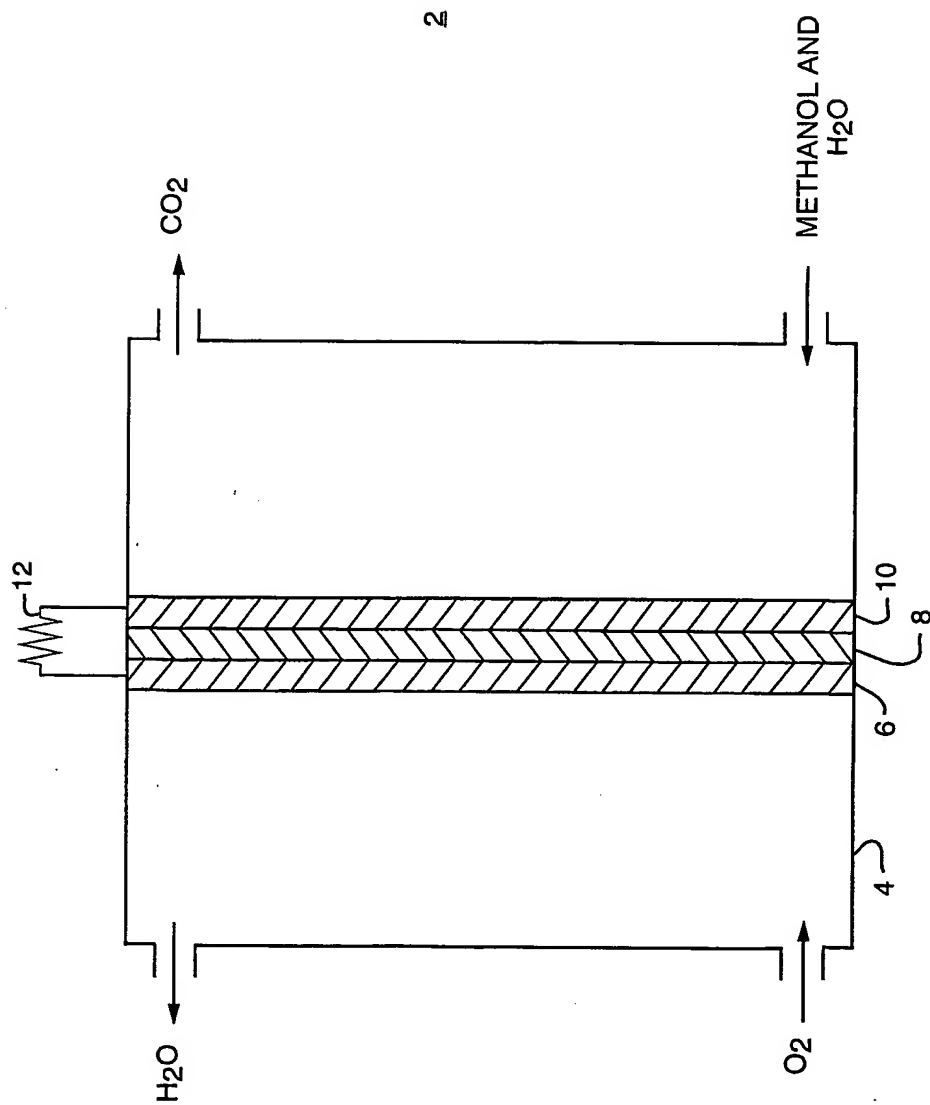
1   15.    The system as in claim 13 wherein said concentration regulator comprises a me-  
2 tering valve, a pump, or a combination thereof.

1   16.    The system as in claim 13 wherein said detector detects changes in a potential  
2 across a load connected to said fuel cell and determining an amount time needed for said  
3 potential to begin to decrease or a rate of decrease of said potential.

1   17.    The system as in claim 13 wherein said detector detects changes in a potential  
2 across a portion of the fuel cell stack.

1   18.    The system as in claim 13 wherein said detector detects changes in a potential at a  
2 portion of an anode of said fuel cell which is proximate to an end of a methanol flow  
3 path.

- 1 19. The system as in claim 13 wherein said detector detects changes in an open circuit
- 2 potential of said fuel cell.





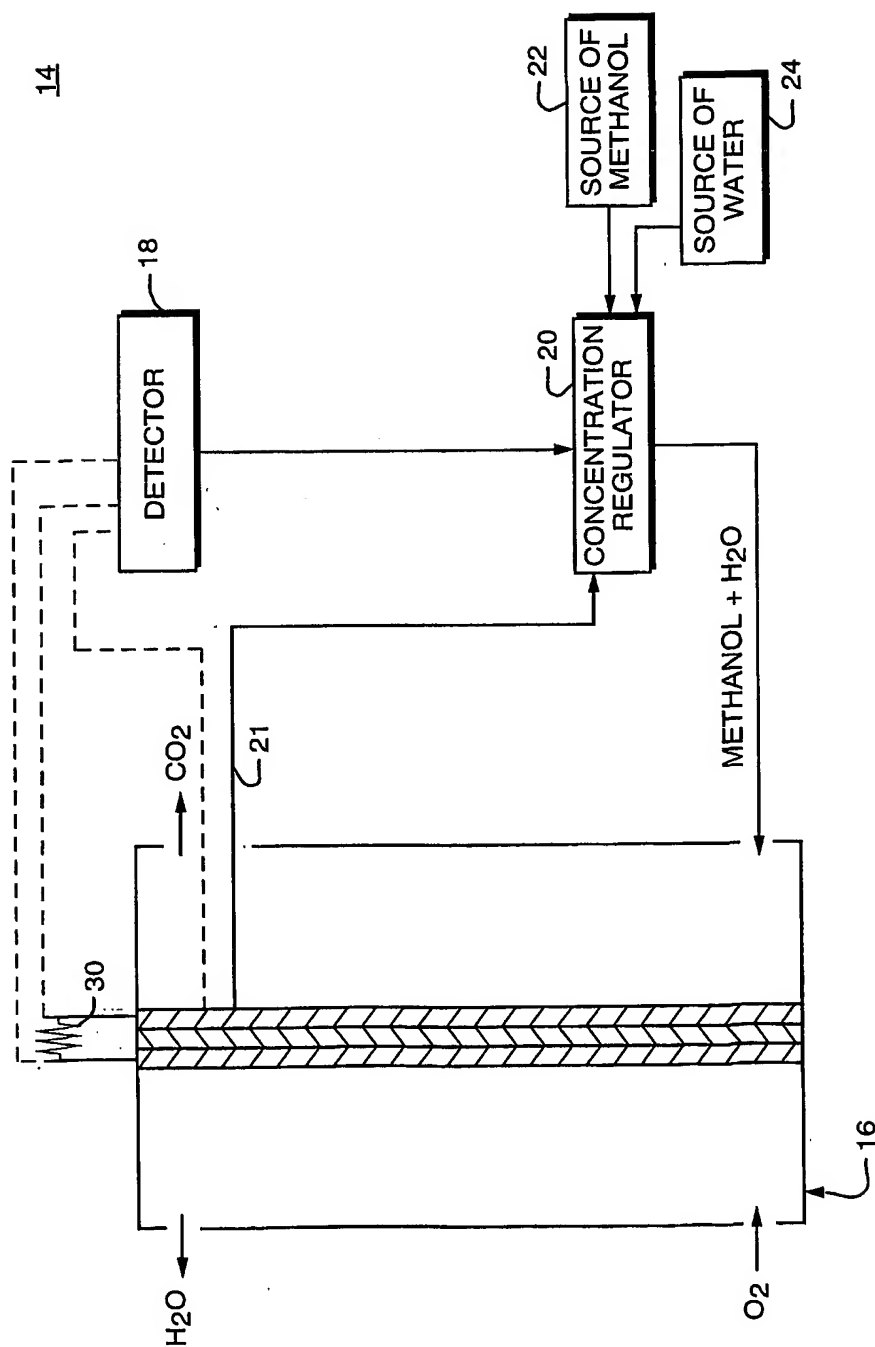


FIG. 2

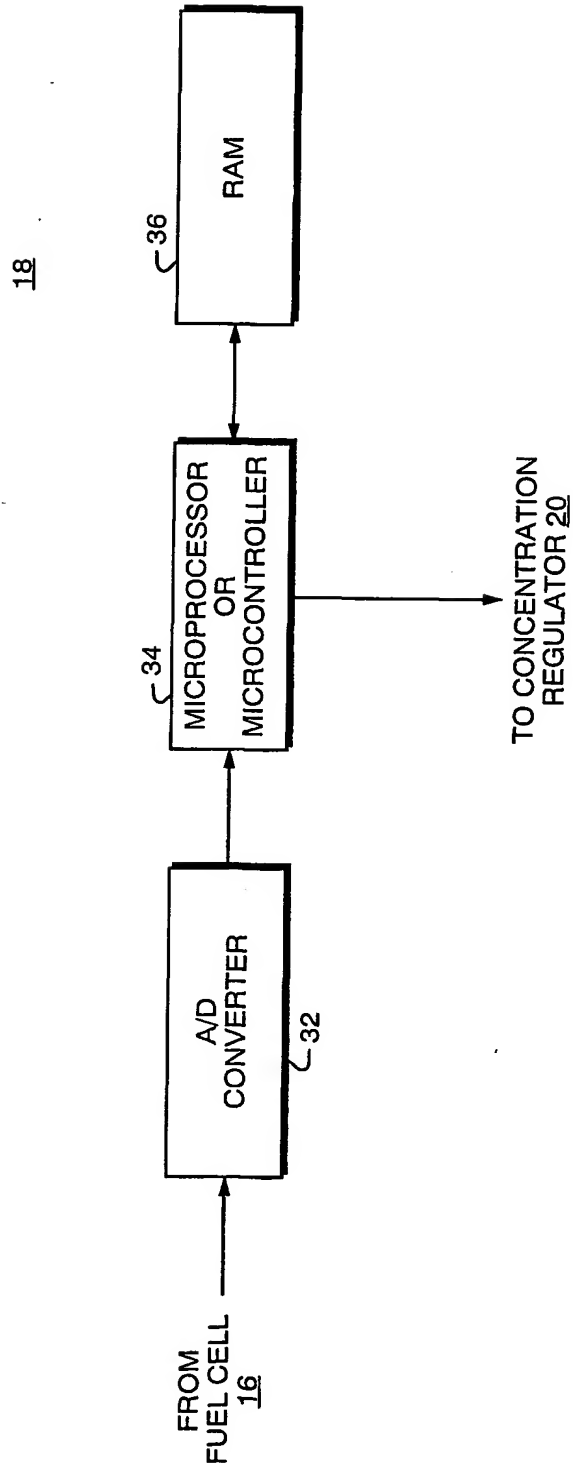
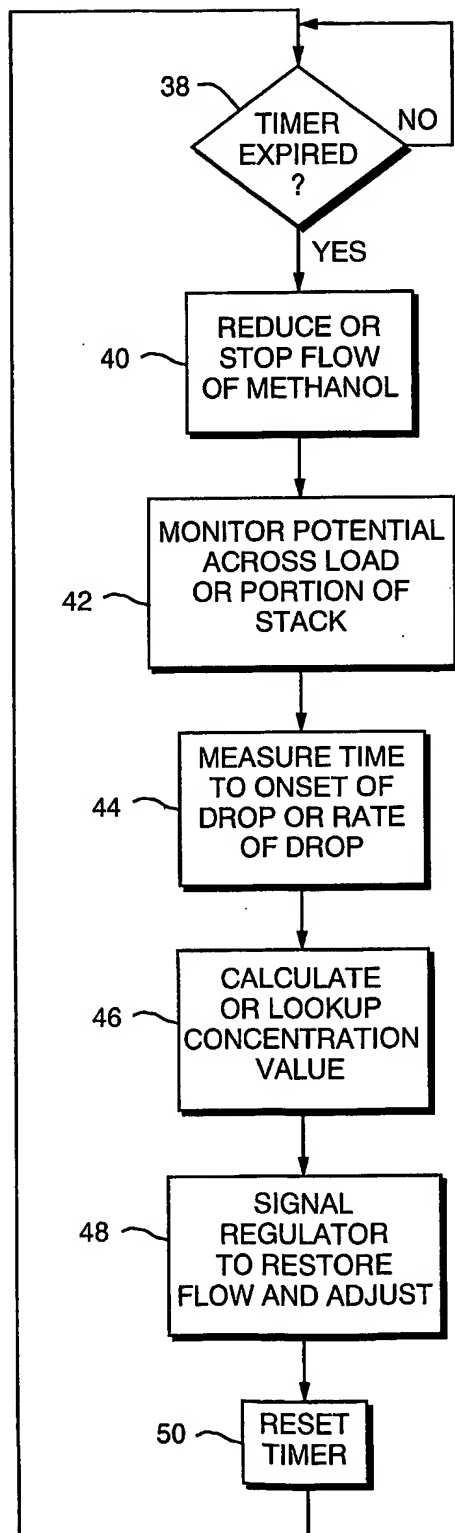


FIG. 3

4/9



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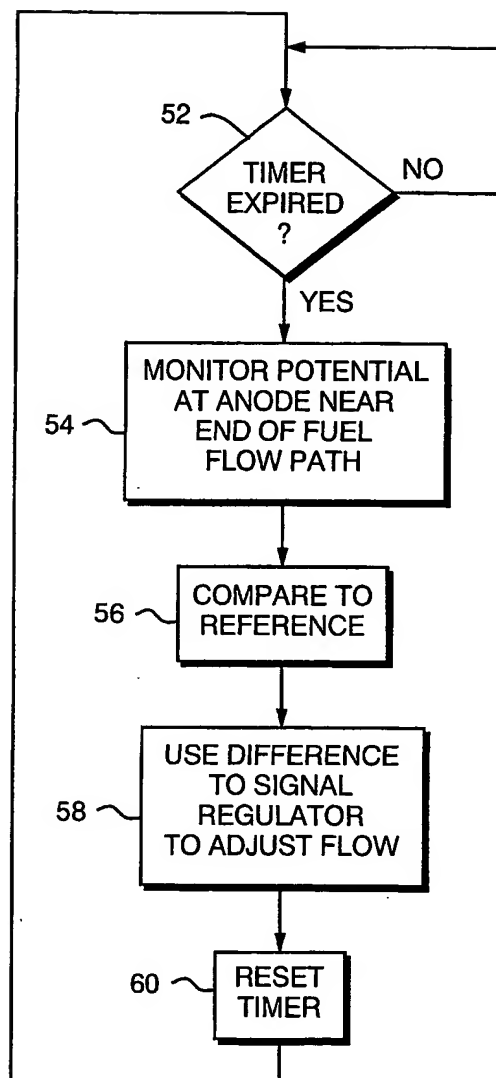


FIG. 5

6/9

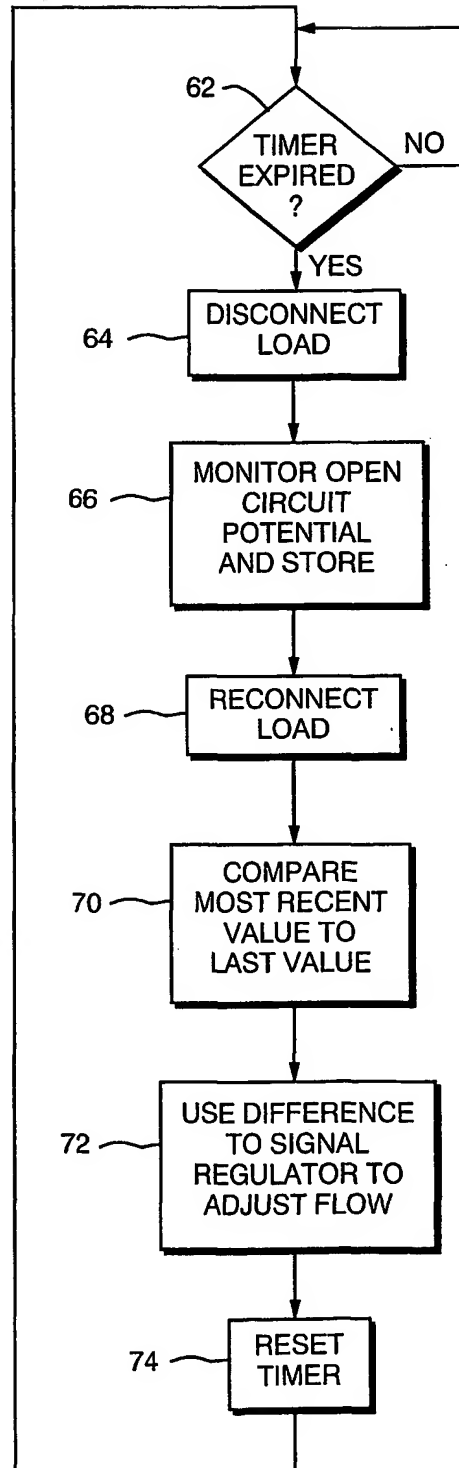


FIG. 6

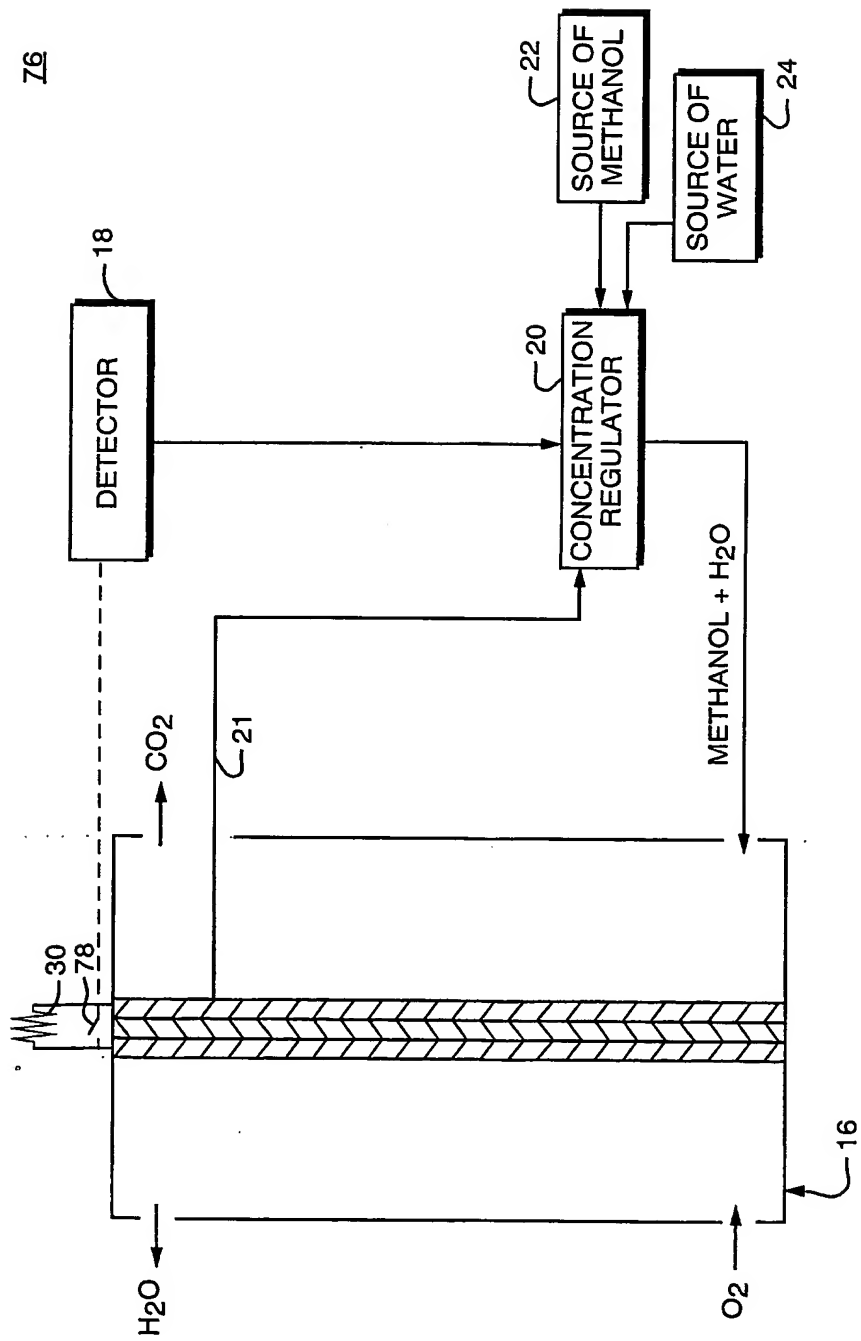


FIG. 7

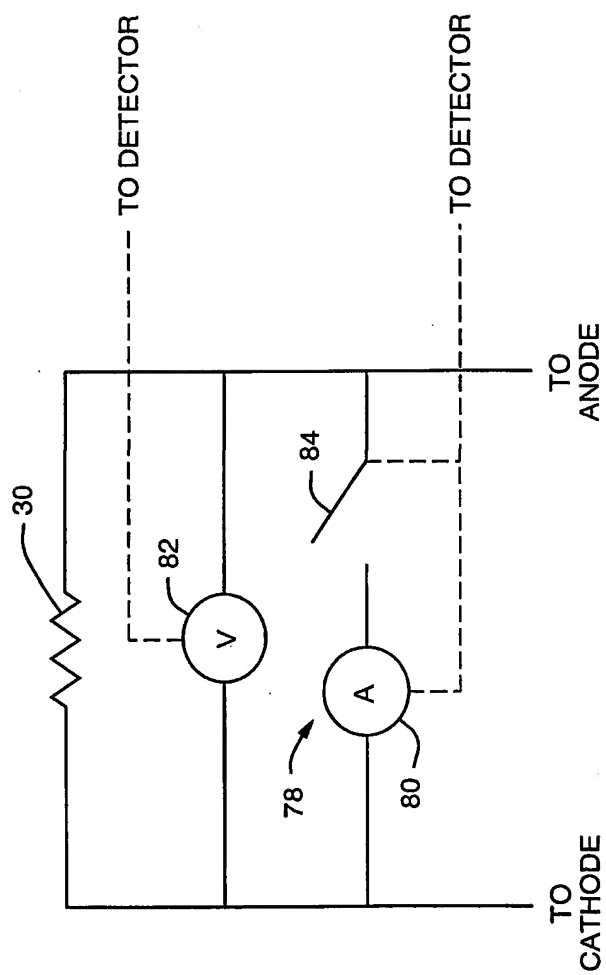


FIG. 8

9/9

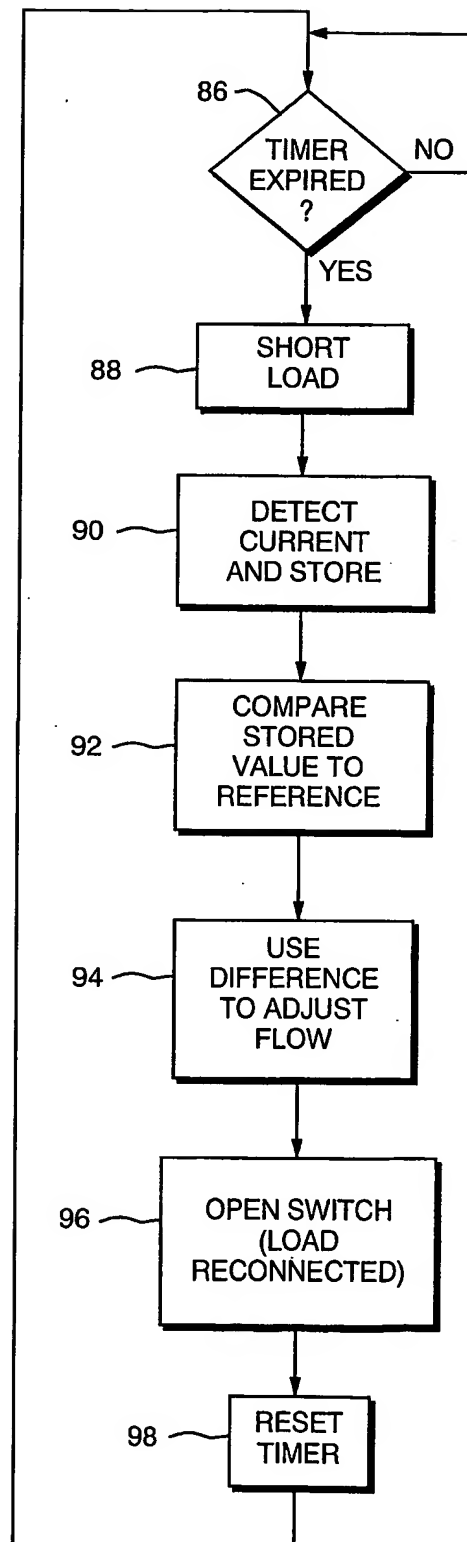


FIG. 9